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13. ABSTRACT (Maximum 200 words)

The broad goal of this project is to formulate mathematical models which are sufficiently general to support an analysis of particular algorithms for target detection and recognition from the perspective of classical statistics and information theory. When approached from this viewpoint, questions about the performance of an algorithm for detection, recognition or identification translate into familiar problems in estimation, complexity and hypothesis testing. Consequently, an arsenal of powerful results from statistics and information theory, for example results about optimal codes, most-powerful tests, inference and efficiency, and the complexity of testing highly composite hypotheses, can be exploited to achieve a deeper understanding of the ATR problem. The focus of the research is on performance metrics, various measures of an algorithms performance such as probability of detection, probability of "false alarm," bias/variance tradeoffs for algorithms that learn from training data, and computational complexity.

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FINAL PROGRESS REPORT

Vision Strategies and ATR Performance: A Mathematical/Statistical Framework and Critique

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Problem Studied

The broad goal of this project is to formulate mathematical models which are sufficiently general to support an analysis of particular algorithms for target detection and recognition from the perspective of classical statistics and information theory. When approached from this viewpoint, questions about the performance of an algorithm for detection, recognition or identification translate into familiar problems in estimation, complexity and hypothesis testing. Consequently, an arsenal of powerful results from statistics and information theory, for example results about optimal codes, most-powerful tests, inference and efficiency, and the complexity of testing highly composite hypotheses, can be exploited to achieve a deeper understanding of the ATR problem.

The focus of the research is on performance metrics, various measures of an algorithms performance such as probability of detection, probability of "false alarm," bias/variance tradeoffs for algorithms that learn from training data, and computational complexity.

Summary of Key Results

Performance Bounds and Theoretical Performance Analysis

An explicit goal of the project is the determination of *lower bounds* for various measures of performance: *What is the best performance that one can possibly achieve within a generic class of algorithms?*

D. Geman and colleagues have proved that coarse-to-fine (CTF) testing is computationally optimal under a certain statistical model. More specifically, there is a certain classifier for a generic object class (e.g., face or truck) and this classifier may be evaluated (computed) in a great many ways. The classifier is based on a family of "tests." Each way of evaluating the tests sequentially and adaptively, stopping when the state of the classifier is determined, corresponds to a decision tree. Each tree (evaluation) has therefore exactly the same error rates, as it is merely a way of evaluating a fixed function. But the trees have widely varying computational costs. Here one assumes each test has a certain "algorithmic cost." We have proven that under a certain model for the joint distribution of the tests under the hypothesis of "no object," a "coarse-to-fine" evaluation is optimal in the sense of minimizing expected cost. The coarse-to-fine refers to the fact that tests have different levels of coarseness in terms of the number of poses of the object they cover. Another, related accomplishment, was an analysis of the false positive rate of the classifier, obtained by making a transformation to a non-homogeneous branching process and then using more or less classical results.

Statistics of Natural Imagery

One cannot meaningfully speak of the *probability of detection* of a target or of the *probability of a false alarm* without making assumptions about an underlying probability distribution on natural scenes. In the language of statistics, this means we need an explicit *null hypothesis* which models generic backgrounds or generic images. Formulating such models has been a major thrust of this contract. A question of fundamental importance is how to specify an appropriate mathematical model for scenes.

In summer 1999, controlled experiments were carried out to collect and categorize a database of laser range images in different settings: forest, residential cityscapes, indoor

scenes, and miscellaneous others. Following the data collection, systematic data analysis was performed to learn empirical distributions of a variety of image statistics. The particular analyses done were motivated by earlier striking findings of scale-invariance properties of reflectance images. Finally, various mathematical models, both *descriptive* ones and *generative* ones, were proposed and analyzed for their potential to adequately represent the empirical results for the range image data set. (Descriptive models describe analytically the essential properties of the low-dimensional marginal distributions of the image statistics, while generative models incorporate, in addition, the direct connections between those marginal distributions and the geometry and spatial arrangement of objects in the 3D world giving rise to the distributions.)

Other groups have started with the assumption that wavelet decompositions of images are the best way to describe their statistics. We do not believe this is true because we find complex dependencies between pixels and between wavelet coefficients which reflect the preferred geometries of the world. This can be understood by contrasting it with the (false) assumption that natural images are white noise: this would say that all pixels are independent and there is no geometry in scenes. The wavelet point of view says there is very simple geometry but it, too, can be eliminated by taking a suitable filter basis for images. Our approach is to look at large numbers of local 3 by 3 patches both in optical and range images, and describe directly their full joint statistics. This was begun in Huang's thesis and has been extended greatly by Lee and now Pedersen, a visiting graduate student from Denmark. The results are very striking: the empirical distribution of high contrast 3x3 patches has a singular surface along which it has infinite density and in whose neighborhood about half such patches are located. This surface is highly curved and represents images of ideal edges. Thus even a simple geometry in the image plane, a geometry of straight edges, produces a very complex cluster in the vector space of local images.

Clutter Modeling

A principal motivation for studying statistics of natural images is the group's objective of developing realistic and usable mathematical models for clutter in natural images; indeed, the generative models for natural image statistics mentioned above are clutter models. The objective of understanding and modeling clutter was stated in the original proposal and received steady attention throughout the project. For example, Grenander's work on modeling clutter in SAR imagery was reported in an early review meeting. In addition to the new work on generative models for image statistics, Grenander recently introduced the so-called *transported generator model*. The model is a simple one and has the potential to form the foundation of more ambitious clutter-modeling work.

A variety of approaches to expand and improve the models were explored, representing different individual views. Grenander outlined a plan for attacking the clutter-modeling challenge—a plan that his recent work instantiated. Essential elements of the plan include (1) experiments with real data, (2) design of models tuned to different categories of scenes (forest, desert, cityscape…), (3) linkage of the models to the sensor modality (IR, laser radar, SAR, reflectance…), and (4) using the models for algorithm design and performance analysis.

Compositional Models

Compositionality refers to the evident ability of humans to represent knowledge through a hierarchy of part-whole relationships. This is widely believed to be the basis for language representation, and many believe that it is in fact a fundamental organizing principle of cognition. One of the main thrusts of the MURI effort has been to explore the implications of a compositional formulation of the machine vision problem: What are the fundamental computational limitations? What are the implications for performance, in terms of "learning" (parameter estimation) and recognition accuracy?

The first step is to formulate the idea of compositionality as a precise mathematical theory of representation. This has been largely achieved, through a rigorous probabilistic formulation, and there is now the beginning of a theory of inference (learning). Shih-Hsiu Huang, a Ph.D. student, completed a software implementation of a ``composition machine." The key contribution of the thesis is a coarse-to-fine computational strategy that yields, *at any instant*, an approximate image interpretation.

A continuum formulation was worked out, and this yielded a surprising connection to what is known as "scaling" in natural images. The latter refers to the remarkable observation that the statistics of natural images are essentially invariant to scale: "blowing up" or "reducing" pictures of natural scenes preserves the statistical structure. Scaling requires a very specific distribution on the sizes of objects in the image plane. We discovered that compositional systems require the same distribution in order to show scaling.

In the language of formal grammars, our composition system amounts to a probabilistic treatment of context-sensitive grammars. This connection is the basis for an ongoing collaboration with computational linguists. The principles of compositionality make specific predictions about the nature of neuronal circuitry and the physiological solution to the so-called "binding problem." This connection is the basis for an ongoing collaboration with neuroscientists.

Given a (probabilistic) compositional model, the problem of scene interpretation becomes one of assigning each element of the scene to a compositional structure in such a way that the resulting collection of such structures maximizes probability. This is formally equivalent to the well studied "covering problems," which is known to be NP-Complete. This brings the computational aspect of computer vision into sharp focus: the basic problem of segmentation, which is a problem that must be solved, simultaneously, at each of many levels of abstraction (which edges go together, which contours are related, which textured patches are part of the same surface, what are the object delineations, which objects are related in a larger "context"...) amounts to the problem of choosing a best covering, and there is no known *general* polynomial-time solution.

Of course, compositional systems have a very special structure and, furthermore, it is clear enough that natural vision systems continuously find good (perhaps nearly optimal) interpretations of scenes. What sort of computational engine can attack the covering problem so effectively? Greedy algorithms can not work---the problem of "what goes with what" is locally ambiguous, which essentially rules out incremental optimization. Monte Carlo methods are universal, but much too slow for high-dimensional problems with complex structure. Dynamic programming, *per se*, doesn't apply because there is no Markov structure---the problem of scene interpretation is fundamentally global.

The scaling properties of natural imagery, and the closely related scaling properties of formal compositional systems, together with the apparent multi-resolution aspect of

feature detection in natural vision systems, strongly suggests a coarse-to-fine computation engine. How efficiently can coarse-to-fine processing solve the image interpretation problem?

This leads, more broadly, to the study of coarse-to-fine computation, and to an effort to make precise the achievable gains in computational speed. These issues were explored both for compositional systems and for closely related Markov systems with very large state spaces. The latter amounts to an analysis of exact coarse-to-fine dynamic programming for general graphical models.

Dynamic programming is the basic computational engine behind the use of hidden Markov models and their generalizations. Brian Lucena, a Ph.D. student, completed a mathematical analysis of a wonderful ``coarse-to-fine" approach to dynamic programming, introduced recently by one of our former students, Chris Raphael. Brian is now working on a new class of computationally efficient error-correcting codes.

In ongoing work, an analysis of the fundamental computational limitations inherent in the vision problem will continue. Specifically, coarse-to-fine algorithms will be the focus of experiments and theoretical analysis. Preliminary experiments suggest that, as a rule, exponential speed-ups are available both in the compositional and the Markov (dynamic programming) settings.

Learning and Recognition

A comprehensive neural network model for learning, detecting and recognizing objects has been developed, and applied to the analysis of complex visual scenes. Amit and D. Geman base the network model on the sparse binary feature representations, which have been used in the detection and recognition algorithms developed. Learning is based on local Hebbian learning rules and is carried out in a central module. Robustness to variations in pose is obtained by using `complex' units that perform an ORing operation over small neighborhoods of the input feature layers over a coarser resolution array. Translation invariant recognition and detection are obtained by hard wiring the appropriate shifting mechanisms. Every shift of the reference grid on the coarse resolution array is copied to allow processing in terms of interactions with the central module. The massive input from the lower layers into higher layers is dealt with through gating mechanisms. Either a specific set of feature/location pairs is gated to allow for detection, a particular shift is gated to allow for classification of the data at a particular location in the scene.

The ability to find stable features of varying degrees of complexity on objects and their sparsity in background allows us to choose from a family of algorithms according to various specifications of failed detection and false positive probabilities. The false positive analysis follows very cleanly from the Poisson statistics, and does not require massive testing on background images.

This approach has been applied to face detection in real scenes, detection of rigid 3d objects in real scenes, detection of symbols in highly cluttered artificially generated scenes. False positive / false negative curves can be predicted using the statistical properties in all these cases.

Compression

Associated with any connected planar region having a sufficiently nice boundary, there is a set of orthonormal functions that are adapted to the region, namely the eigenfunctions

of the Laplacian. These functions reflect the shape of the region and thus suggest themselves possible basis for representing the image. The merit of such an expansion can be evaluated in terms of the number of nonzero coefficients required to achieve a desired level of fidelity. For rectangular regions this specializes to the usual Fourier basis. Of course Fourier series is not particularly useful for non rectangular regions and this is the natural modification. Our experimental work supports the idea that these ideas can significantly improve the bits per pixel and it has been suggested that the coding scheme developed may be consistent with the most recent MPEG standards.

Variational Approach to Bayesian Estimation

Sanjoy Mitter in joint work with Nigel Newton of the University of Essex developed a Variational Theory for Bayesian Estimation which characterizes the conditional distribution as the solution of a variational problem of minimizing a certain Free Energy. This theory is very general and applies to Hidden Markov Models based on a Markov Random Field. This research makes non-trivial connections to recent work on Inference on Graphs, Coding theory and Non-Equilibrium Statistical Mechanics. It has enabled us to solve the long-standing open problem of giving a Variational View of Non-linear Filtering. Several papers describing this work are in preparation.

Temporal Information in Recognition

We developed a coherent statistical/Bayesian framework for tracking of moving objects in highly cluttered environments on the basis of video image sequences. The framework involves three basic components: (i) An object representation, i.e. a model that articulates the overall shape architecture of an object together with the objects random deformations (rigid and non-rigid); (ii) a dynamic model, i.e. a prior on the set of possible trajectories of a moving object; and (iii) an observation model that relates, at each video frame, the image gray-level data to the object and dynamic models, and articulates the random variability of the image data due to clutter, occlusion, and other image degradation. The combination of these three components leads to a nonlinear filtering problem which is equivalent to a Hidden Markov Model (HMM). We have explored two object representations (a deformable template model, and a hierarchical syntactic model), and two observation models-- a nonlinear one that explores the HMM representation of the filtering problem, and a linear one that employs the hierarchical/syntactic models. The nonlinear observation model is combined with a Monte Carlo based tracking algorithm and runs in real time. The linear observation model is combined with the Extended Kalman Filter (EKF), but at the present time it does not run in real time. Our experiments demonstrate that the Monte Carlo filter performs considerably better than the EKF in cluttered environments; the performance of the two filters is comparable in environments with limited image degradation.

Data-Driven Performance Optimization

The guiding principle of *minimum description length* has been espoused as means of inferring compositional structure in scenes by members of the group from all five participating universities. R. Brockett and colleagues at Harvard have developed ways of using *feedback* about the gradient of description length (or other measures of the complexity of the description of an image) during an iterative computation as a way of tuning or adapting a vision algorithm's parameters optimally for the particular scene being processed. The use of feedback in this setting is reminiscent of the use of feedback loops in control theory. The versatility of the approach to data-driven

performance optimization has been demonstrated on algorithms for (1) region-based image compression and (2) extraction of coherent structure from highly cluttered scenes.

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Report of Inventions

None.

Bibliography

Please see the previous list of Publications supported by this grant.